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SP 1804-DR(11-77)

SAND-78-0209
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Printed March 1978

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DISTORTION OF PLASMA DIAGNOSTICS BY AN AMBIENT GAS

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ABSTRACT

The effect of vacuum chamber background gas on the ion measurements of a laser-produced, expanding plasma is studied over a wide range of background gas pressures. Experimental measurements are compared with calculations from a coupled rate equation-hydrodynamics code. The code is then used for a parametric study of the effect of background gas pressure on plasma diagnostic measurements. Charge exchange is found to be an important process in our diagnostics above vacuum chamber pressures of 10^{-5} Torr.

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$3.50; Microfiche \$3.00

With the increased emphasis on evaluation of high temperature plasmas in fusion research and related areas, diagnostic techniques for characterizing plasma emission and expansion have taken on additional significance. The correct interpretation of diagnostic measurements requires not only calibration with known sources, but also cognizance of conditions in the experimental system and the diagnostics which can significantly affect the data. For example, secondary emission, collector surface conditions, and even the vacuum chamber background pressure all may have a significant effect on the signal acquired with Faraday cup ion diagnostics. The effect of secondary emission has been evaluated previously for a variety of Faraday cup configurations.¹ An estimate of the effect of vacuum chamber background gas on the ion diagnostics is important because the configuration and composition of the diagnostics in many target chambers limits the minimum background gas pressures to the 10^{-5} to 10^{-4} Torr range. In this paper we will concentrate on the effect of vacuum chamber background gas on Faraday cup and Thomson Parabola measurements of ion expansions from laser-created plasmas. The plasmas were measured under a variety of vacuum chamber pressures. These experimental results were then used to normalize a plasma kinetics code which was coupled to a one-dimensional hydrodynamics code. The code, in turn, was used to predict the impact of a wide range of background pressures on plasma diagnostics.

The experimental evaluation of background pressure effects employed a Nd:glass laser operating at 2.7×10^{14} W/cm² to irradiate a thin film (exploding pusher) planar polystyrene target. The plasma expansion was detected with Faraday cups¹ and a Thomson Parabola². The axis of the

Thomson parabola was normal to the target. The Thomson parabola uses parallel electric and magnetic fields to separate ions according to their charge/mass ratio and their energy. For CH plasmas, this device permits unique identification of all significant plasma species. A schematic of the experiment is shown in figure 1. The Faraday cups and the Thomson parabola were located at distances of 30 cm and 100 cm, respectively, from the polystyrene target. The vacuum pressure was varied between 1×10^{-5} Torr and 4.2×10^{-4} Torr by permitting air to bleed into the chamber and controlling the pumping rate.

Ion current traces measured by Faraday cups at two different pressures (with all other conditions the same) are shown in figures 2(a) and 2(b). Comparing the lower traces of 2(a) and (b), an increase in the pressure from 1×10^{-5} Torr to 4×10^{-4} Torr leads to a reduction in signal by about a factor of two. The Thomson parabola measurements provide the capability for a more detailed interpretation of background gas effects, since a rough evaluation of the species distribution as a function of gas pressure can be obtained. Densitometer evaluations of Thomson parabola photographs for three different background pressures are given in figures 3(a)-3(c). At the 4.6×10^{-5} Torr (fig. 3a), C^{+1} through C^{+5} are present with the dominant ionization states being C^{+3} , C^{+4} and C^{+5} . When the pressure increases to 2.1×10^{-4} Torr (fig. 3b), C^{+4} and C^{+5} have essentially disappeared and the dominant species are C^{+1} , C^{+2} and C^{+3} . Increasing the pressure still further to 4.2×10^{-4} Torr (fig. 3c), the dominant observed charge states are C^{+1} and C^{+2} . Thus, a background pressure increase from 4×10^{-5} to 4×10^{-4} Torr results in a change of the average charge detected by the diagnostics from $\bar{Z} \sim 4$ to $\bar{Z} \sim 1.25$.

It is proposed that this decrease in observed $\bar{Z}$ can be related to charge exchange between the expanding plasma and the background gas in the vacuum chamber. To test this concept, the charge exchange mechanism was added to a plasma kinetics code which correctly handles ionization and recombination rate processes³. Most of the charge exchange cross sections for the multiply ionized states of carbon have not been experimentally determined over the energy range important in our plasma expansions. The cross sections which are available include the recent measurements of the charge exchange of C^{+1} with H_2 by Lockwood, Miller, and Hoffman⁴, the calculation of charge exchange of C^{+n} with H by Olsen and Salop⁵, and the measurement of C^{+n} charge exchange with H_2 by Meyer and Phaneuf⁶. To model the presence of air in the vacuum chamber, we assume the background gas to be H_2 . Since there is no adequate scaling theory to estimate the $C^{+n} - H_2$ cross sections from the $C^{+n}-H$ and $C^{+n}-H_2$ cross sections, we simply multiplied the H_2 cross sections by the ratio of the Lennard-Jones rigid sphere cross sections for H_2 and H_2 ⁽⁷⁾ and estimated the $H_2:H$ cross section ratio by comparing results from References 5 and 6 at a relative velocity of 3×10^8 cm/s. Values of these measured and estimated cross sections are shown in Table 1 for C^{+n} energies from 15.6 to 560 keV. All of the cross sections used in these estimates are single-electron capture cross sections. Multi-electron charge exchange processes are assumed to be unimportant.⁸ We note that the data in References 5 and 6 suggests that for a velocity greater than 2×10^8 cm/s, the single electron capture cross sections increase as the projectile charge state increases.

The comparison of the code results (solid line) with the experimental measurements (discrete points) is shown in figures 4(a), 4(b), and 4(c)

for a range of background gas pressures. For all of these comparisons the cross sections have been uniformly increased by a factor of 2. The experimental points are determined qualitatively by evaluating the Thomson parabola traces as follows: an intense trace is assigned a value of 1.0, a trace just above threshold corresponds to a value of 0.1, and traces with intermediate intensities are assigned values of 0.5. A more detailed analysis of these traces is not warranted due to the several sources of non-linear response in the Thomson parabola device.⁹ For a pressure of 4×10^{-5} Torr (fig. 4a), the experimental and computational trends are similar, but the calculations predict that the average charge state is one higher than that observed experimentally. At higher pressures the agreement between code calculations and experimental results is acceptable (figures 4b and 4c). No attempts were made to improve agreement between experiment and theory by further adjustment of the charge exchange cross sections because of the qualitative nature of the analysis. With the charge exchange cross sections thus normalized to the experimental results for a variety of background gas pressures, it is now possible to study the effect of the vacuum chamber conditions over a much wider range of pressures. Because of the limitations noted earlier, these extrapolations beyond the results of the present experiments are interesting for the trends which may be observed.

The results of a broad range parameterization for a carbon plasma are shown in figure 5. With no background gas (I), the fully ionized C^{+6} species dominates the plasma expansion. When the pressure is raised to 1.2×10^{-7} Torr (0), very little change is observed. As the pressure increases, first the concentration of C^{+5} becomes roughly equal to the

concentration of C^{+6} (1.2×10^{-5} Torr, ■), and then the amount of C^{+6} becomes only a small percentage of the quantities of C^{+3} and C^{+4} (1.5×10^{-4} Torr, ♦). Finally, at pressures above 2×10^{-4} Torr, the lowest charge states dominate the carbon ion species distribution.

The impacts of this trend are twofold. First, it is apparent that species distribution and ion expansion information should be collected at vacuum pressures below 10^{-5} Torr. Second, at higher pressures, it appears that a significant number of neutral atoms are created through charge exchange. Thus the analysis of data from the charge detectors such as Faraday cups, Thomson parabolas, and magnetic spectrometers which attempt to obtain a plasma energy balance through ion collection can produce erroneous results.

In summary, experiments have been carried out to determine the effect of vacuum chamber background gas on the measurement of the expansion from a laser-produced plasma. The results, which indicate a significant change in the species distribution, are used to normalize the charge exchange cross sections in a plasma species kinetics code which has been coupled to a one-dimensional hydrodynamics code. This code is then used to study the impact of background gas over a wide range of pressures. The code predicts that substantial diagnostic errors will occur in our diagnostics for gas pressures greater than 10^{-5} Torr.

ACKNOWLEDGEMENTS

The authors would like to thank Dra. B. Ripin and R. Decoste for early discussions on the importance of the charge exchange mechanism, J. M. Hoffman for discussions on the charge exchange cross sections, M. A. Palmer for his densitometer work, and J. Lavasek and M. Dillon for their technical assistance.

FIGURE CAPTIONS

Figure 1. Experimental schematic. The Nd:glass laser strikes the target at 17° from the target normal. The Thomson parabola and Faraday cup were 0° and 17° , respectively, from the target normal.

Figure 2. Faraday cup currents at a vacuum chamber background gas pressures of 1×10^{-5} Torr (2a) and 4×10^{-4} Torr (2b).

Figure 3. Densitometer traces of the Thomson parabola photographs for vacuum chamber background gas pressures of 4.6×10^{-5} (3a), 2.1×10^{-4} (3b), and 4.2×10^{-4} Torr (3c). The lower trace in each figure is H^+ .

Figure 4. Comparison of the code results (solid line) with the experimental results (discrete points, see text for a description of their determination). Parts (a), (b), and (c) represent vacuum chamber background gas pressures of 4×10^{-5} , 1.5×10^{-4} , and 4×10^{-4} Torr, respectively.

Figure 5. Calculation of the relative number of a particular charge state of carbon as a function of vacuum chamber background gas pressure. The points represent pressures of 0.0 (X), 1.2×10^{-7} (o), 1.2×10^{-6} (Δ), 1.2×10^{-5} ($\blacksquare$), 1.5×10^{-4} ($\blacklozenge$), 2.6×10^{-4} ($\bullet$), and 5.1×10^{-4} Torr (∇).

EXPERIMENTAL SCHEMATIC

Figure 1

Figure 2

4.6×10^{-5} torr

Figure 3a

2.1×10^{-4} torr

Figure 3b

4.2×10^{-4} torr

Figure 3c

COMPARISON OF CODE WITH EXPERIMENT

Figure 4

Figure 6

Table 1. Charge exchange cross sections for $C^{+n} + A \rightarrow C^{+(n-1)} + A^+$, in units of 10^{-16} cm^2 .

$E(\text{keV})$	$1 \rightarrow 0$	$2 \rightarrow 1^{(c)}$	$3 \rightarrow 2^{(c)}$	$4 \rightarrow 3$	$5 \rightarrow 4$	$6 \rightarrow 5^{(b)}$
15.6	5.9 ^(a)	20	5	20*	38*	89
62.3	10.8 ^(a)	15	10	20*	38*	89
140.0	8.5 ^(c)	11.3	15	20*	38*	68
249.0	6.2 ^(c)	9.4	17.6	20*	38*	57
389.0	4.1 ^(c)	7.9	17.6	20*	38*	49
560.0	2.5 ^(c)	6	12.5	20 ^(c)	38 ^(b)	44

(a) $C^{+n} + H_2$ from Reference 4

(b) scaled from Reference 5, $C^{+n} + H$

(c) scaled from Reference 6, $C^{+n} + H_2$

(*) data not available, assumed constant as a function of energy

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